

What is the Issue with SN1987A Neutrinos?

F. VISSANI¹, M.L. COSTANTINI², W. FULGIONE³,
A. IANNI¹ and G. PAGLIAROLI¹

¹INFN, Gran Sasso, Assergi (AQ) Italy

²ICRANet, Pescara (PE) Italy

³Ist. di Fisica Spazio Interplanetario (INAF)
and INFN, Torino (TO) Italy

Abstract

What did we learn out of SN1987A neutrino observations? What do we still need for a full understanding? We select important issues debated in the literature on SN1987A. We focus the discussion mostly on the relevance of certain data features; on the role of detailed statistical analyses of the data; on the astrophysics of the neutrino emission process; on the effects of oscillations and of neutrino masses. We attempt to clearly identify those issues that are still open.

1 Introduction

In the occasion of SN1987A event, several detectors claimed interesting observations. LSD (90 t of scintillator, 200 t of iron) found 5 events before the astronomical alarm [1] and, in the few hours around this observation, an anomalously large number of correlations between individual counts of different neutrino telescopes and the temperature fluctuations of gravity wave detectors, see [2]. After 4.5 hours, other three detectors found bursts of events, simultaneous within errors and thus attributable to the same phenomenon. These are:

• Kamiokande-II (H ₂ O, 2140 t) [3]	11 or 16 events
• IMB (H ₂ O, 6800 t) [4]	8 events
• Baksan (C ₉ H ₂₀ , 200 t) [5]	5 events
Total	<hr/> 24 or 29 events

Here we quote the events occurred in a 30 s window. In small characters we show the events of Kamiokande-II occurred in a smaller time window, above the energy threshold and located in the fiducial volume; however, these 3 quantities have been chosen *a posteriori* rather than *a priori*. The discrepancy in time with LSD could indicate a 2 stages emission and collapse; however, no satisfactory model for such

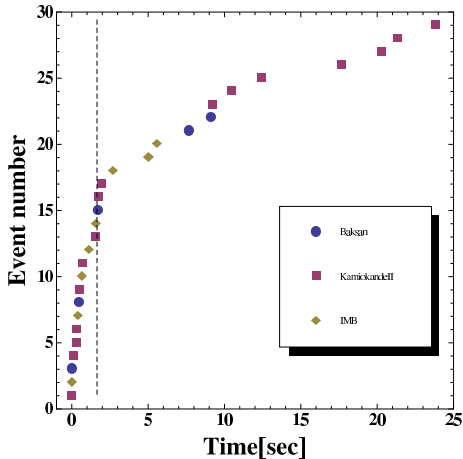


Figure 1: *Cumulative time distribution of all SN1987A events. The vertical line marks the time where we have half of the sample. In the first second Kamiokande-II (purple squares), IMB (brown diamonds) and Baksan (blue circles) saw a large number of events: 6, 3 and 2 respectively, i.e., 30% of the sample.*

an emission is available yet. Thus, we postpone the interpretation of LSD events and focus the discussion on the second group of 29 events, which following the common lore are attributed to supernova (SN) neutrino emission. The literature includes many discussions on the energy and angular distributions of the IMB and Kamiokande-II events; we claim that neither of them deviates significantly from the expectations, as summarized in [6]. Much more interesting is the time distribution of these events, that has a *steep initial ramp*: see Fig. 1. We will discuss this later.

2 Statistics for SN1987A

Although one can separate signal from background events only on statistical basis, it is not possible to attribute all 29 events to noise. We find [7, 8] that Kamiokande-II has an evidence of SN burst more significant than 10σ , as widely acknowledged, i.e., by the Nobel prize committee. Thus, one should use these events to learn on the nature of neutrino emission. For small event samples, the best we can do is to use a Poisson likelihood [9]; we recall its construction. Consider the expected event number in the i^{th} bin as function of some parameters denoted by θ :

$$n_i = n_i^{\text{bkg.}} + n_i^{\text{sign.}}(\theta) \quad (1)$$

where the 1^{st} (2^{nd}) contribution is due to background (signal). Since the probability in the i^{th} bin is $P_i = e^{-n_i}$ if no events are seen and $P_i = n_i e^{-n_i}$ if 1 event is seen there, the likelihood is just:

$$P(\theta) = \prod_i P_i = e^{-\sum_j n_j} \times \prod_{i=1}^N n_i \quad (2)$$

The first term (the exponential) depends on the total number of expected events and it is a purely theoretical quantity, and the second term (the product) encodes the information on the observation in the specific set of N bins that contain one event. We model the detector in ‘linear response’ writing

$$n_i^{\text{sign.}}(\theta) = \sum_j R_{ij}^{\text{det.}} \times n_j^{\text{ideal}}(\theta) \quad (3)$$

where $R_{ij} \equiv G_{ij} \times \epsilon_j$ is the response function and $\epsilon_j \equiv \sum_i R_{ij} \leq 1$ the efficiency. Lamb and Loredó 2002 [11] proposed a different prescription, which biases the analysis [9]. Different statistical prescriptions, Bayesian in [11] and frequentist in [8], introduce only small differences in the results instead [9].

3 Astrophysics and Model of Neutrino Emission

The core collapses of stars above $\sim 8M_\odot$ form compact stellar objects: neutron stars, hybrid (quark) stars—perhaps—and black holes. The released kinetic energy, $\sim 10^{51}$ erg, imparted to the shells surrounding the core, leads to a wide variety of optical supernovae: SN II, Ib and Ic. An enormous binding energy, 10 – 20 % of the core rest mass, to be sure

$$\mathcal{E}_{\text{bind}} \sim G_N M^2 / R = 3 \times 10^{53} \text{ erg} \quad (4)$$

for $M = M_\odot$ and $R = 10$ km, has to be carried away to permit the formation of the compact object. A principal role of neutrinos is to fulfil this task.

Black body approximation The neutrino luminosity of the hot compact object is impressive already in black body approximation: $L_{\text{cool}} \sim R_c^2 T_c^4 = 5 \times 10^{51} \text{ erg/sec}$ when $R_c = 10$ km and $T_c = 5$ MeV. T_c is the neutrino temperature in the region where the object becomes transparent, called “neutrino-sphere”, with radius R_c . Such a luminosity correctly indicates the time scale of neutrino emission:

$$3 \times 10^{53} / [6 \times (5 \times 10^{51})] = 10 \text{ sec} \quad (5)$$

where “6” are the neutrino types: $\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu$ and $\bar{\nu}_\tau$. But, evidently, the black body formula: $dN_\nu = \pi R_c^2 c dt \times d^3 p / h^3 / [1 + \exp(E/T_c)]$ is a poor description of the actual physical processes that lead to neutrino emission.

Expected time dependence of the neutrino emission All calculations since [10] found that there is a very intense neutrino emission during a rapid “accretion” phase in the first (fraction of a) second. Astrophysicists are still working to understand it fully. What is the role of this emission? Before answering, it is useful to recall another feature of the existing theoretical calculations: the shock wave initially stalls into the core without triggering the explosion. The main hope is that the stalled shock wave is refueled by the neutrino pressure: namely, a fraction of the 3×10^{53} erg enters the 10^{51} erg budget. This conjecture, called “delayed scenario” for the explosion, *does require* the initial increase of the neutrino luminosity, that can and should be tested by neutrino observations, including those from SN1987A.

Improved model for data analysis Usually, SN1987A data analyses are carried on in black body approximation, thereby excluding any adequate modelling of the physical emission processes, and even worse, considering only the energy distribution. But as we argued it is important to model also the time distribution, including the expected initial $\bar{\nu}_e$ emission. This was first done in [11] and subsequently improved in [8], based on the following simple physical picture: On top of the black body emission region that cools the compact object and during the very rapid initial accretion, there is a dense e^+e^- plasma that causes a release of $\bar{\nu}_e$ via

$$e^+ + n \rightarrow p + \bar{\nu}_e. \quad (6)$$

This initial flux results from an emitting volume, rather than from an emitting surface, as for the black body. The initial flux from the transparent atmosphere around the compact object greatly increases the luminosity. A quantitative check of the luminosity in the two phases shows that with completely reasonable model parameters, the initial luminosity is one order of magnitude larger [12].

4 A New Fit of Kamiokande-II, IMB and Baksan

Our model [8] includes 2 phases of emission, each one with 3 free parameters meaning: the amount of energy emitted, the average energy on the neutrinos, the duration of the phase. The fit has 3 more parameters, describing the unknown time interval between the first neutrino that reached each detector and the first event that has been revealed. The new fit is presented in details in [8] and commented in several talks, e.g., [6, 13]; our parameterization can be downloaded on the web [14]. The fit returns a parameterized flux that, by construction, smoothly interpolates between the 2 emission phases. The result resembles very closely the general expectations and we emphasize the following four points: (a) There is a 2.5σ evidence for the initial emission; this quantifies the hint for “accretion” that we perceive already from Fig. 1. (b) Using the best fit flux, we estimate that the most probable number of signal events that occurred in the detected sample of 29 events is:¹

$$N_{\text{sign.}} = 21.4 \pm 1.2 \text{ signal events} \quad (7)$$

Putting aside any information on the signal, the result is similar: $29 - 5.6 - 1 = 22.4$. (c) The parameters are determined only within large errors, as a consequence of the limited statistics. (d) Finally, at best fit we calculate the emitted binding energy

$$\mathcal{E}_{\text{bind}} = 2.2 \times 10^{53} \text{ erg}, \quad (8)$$

a factor of 2 smaller than the result of the fits based on black body emission only.

¹*A priori*, we expect 5.6 (resp., 1) background events in 30 s in Kamiokande-II (resp., in Baksan) [11, 8]. *A posteriori*, we find that the same is 6.5 ± 0.8 (resp., 1.2 ± 0.9), see [8] (resp., [6]) for details. We obtain these numbers from the probabilities that any individual event is due to background, that can be calculated considering its time, energy and direction, once we know the distributions of the background and of the (best fit) flux.

5 SN1987A, Oscillations and Neutrino Masses

Is large lepton mixing excluded? This question was raised by Smirnov, Spergel & Bahcall [15] who state: “The restrictions $p < 0.23$ (0.35) at 95% (99%) CL can be considered as upper bounds in a representative supernova neutrino burst model.” This is a remarkable claim, since the experiments [16] identified the solution of the solar neutrino problem called “LMA”, that in normal mass hierarchy implies that the conversion probability for supernova neutrinos is $p = \sin^2\theta_{12} = 0.31$. Kachelrieß et al. [17] reach a weaker conclusion: “LMA-MSW solution can easily survive as the best overall solution, although its size is generally reduced when compared to fits to the solar data only.” When we consider the uncertainties in the astrophysical parameters of neutrino emission, the conclusions change even more. In fact, ref. [8] argues that, even including $p = 0.31$, “a value $T_x/T_{\bar{e}} = 1.0 - 1.5$ or a deviation of the amount of energy stored in non-electronic neutrino species by a factor of 2 does not affect crucially the fitted $\bar{\nu}_e$ flux.”

Is earth matter effect important? In [18] Lunardini & Smirnov write: “We show that these effects can provide explanation of the difference in the energy spectra of the events detected by Kamiokande-2 and IMB detectors from SN1987A.” But the 1 layer approximation [19] i.e.,

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \cos^2\theta_{12} + \varepsilon \times \frac{\sin^2 2\theta_{12}}{D^2} \times \sin^2\left(\frac{\Delta m_{12}^2 L}{4E} D\right) \quad (9)$$

suggests that matter effect is not important. In fact, the earth matter effect is enucleated in $D \sim 1$ and in:

$$\varepsilon = \frac{\sqrt{2}G_F N_e}{\Delta m_{12}^2/(2E)} \sim 0.1 \text{ when } \rho = 4\text{gr/cm}^3 \text{ and } E = 20 \text{ MeV}, \quad (10)$$

a good approximation of the full result [20]. In [21] we state that, even at fixed astrophysical parameters: “the inclusion of MSW in the Earth diminishes the expected number of IBD events in KII (respectively in IMB) only by 0.5% (respectively by 2.5%),” which once implies that the Earth matter effect has a negligible role.

Do we have a new twist in oscillations? The subject has a confuse history: 1) Till recently, oscillations were thought to be similar to solar ν oscillations (e.g., Dighe & Smirnov '01 [22]). 2) Today, we agree that they are non linear as argued by Pantaleone in '92 [23]. 3) New simple formulae are proposed [24], but are them safe? Despite many works to discuss this, we do not know it yet. Using the new formulae in our analysis [8] we find: *i*) In normal hierarchy, the formulae are unchanged and thus oscillations do not modify the quality of our fit, $\Delta\chi^2 < 1$. *ii*) Inverted hierarchy seems to lead to some effect but building on an incompleteness of the model used: thus, we have no quantitative conclusion yet.

Are neutrino masses relevant? There have been many discussions on neutrino masses. These were partly informed by the wish to know more on neutrino masses (that have been largely unknown till recently) and partly responded to the direct

interests of the particle physics community, rather than to the wish to understand the meaning of the data. With present information, and in particular with the direct bound resulting from the tritium decay experiments, we reach the neat conclusion that neutrino masses are irrelevant for the interpretation of SN1987A data [25].

6 Main Open Issues

Multiple neutrino emissions? There are 2 ways to have signals in LSD but not in the other detectors: (1) They were very low energy $\bar{\nu}_e$, close to LSD threshold [27]. (2) They were high energy ν_e [28]. The first needs $\sim 1 M_\odot c^2$ in $\bar{\nu}_e$ and in ν_e , an *ad hoc* spectrum and has no astrophysical support; the second implies an intense neutronization of a rapidly rotating object. The next trouble is the nature of the second emission: It could be due to a black hole transition or a hybrid (quark) star transition. But since these ideas are not at the level of the ‘standard model’ discussed above, we are not ready to interpret LSD events.

Missing neutron star? The theory of neutron star cooling predicts an intense X ray source, with luminosity $L \propto R_{ns}^2 T_{ns}^4$ but the existing bound is 4 times below the expectations [29]. There are various ways to avoid the contradiction and among them [29]: 1. The remnant is not standard, e.g., its core shows proton superfluidity or includes strange quarks, and thus it cools faster. 2. The compact object is a black hole. 3. The star is shrouded in dense materials. Any of these imply the presence of an X ray source at *some* level. Possibly relevant points are: the relatively large mass of the progenitor, considerations on the rotation state, again LSD, etc.

7 Summary and Discussion

We discussed SN1987A neutrinos and their interpretation. While we do not pretend to solve all the important problems raised by this epochal observation here, we did our best to settle a number of issues discussed in the literature: 1. Adequate statistical tools to extract most effectively information from small event samples exist and can be usefully adopted. 2. The time distribution of the events seen by Kamiokande-II, IMB and Baksan is particularly interesting and important. 3. These data sets fit nicely in a model built to resemble the standard emission and provide a 2.5 sigma support in its favor, or of something very much alike. 4. There is no evidence yet that ν masses or oscillations are relevant to understand SN1987A observations. There are still open issues, which however do not mean that we will not progress in the understanding of SN1987A before we will observe another supernova.

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Questions

W. Kundt: Is the hypothesis of emission from transparent atmosphere correct?

FV: It is routinely used to model the initial ν_e and $\bar{\nu}_e$ emission, e.g., [30], but as recalled, the existing simulations cannot be considered conclusive. A fraction of about 10% of this emission should be reabsorbed by the the star, if the delayed scenario for the explosion actually works, though such a small effect cannot be tested by SN1987A events. Strictly speaking, the antineutrino emission—and the initial luminosity peak—could be due to some other mechanism, e.g., the one you propose [31]; or to hybrid (quark) star formation [32]; etc. But if this is the case, we would be even farther from knowing what we should compare the 29 events with.

D. Fargion: What is the asymmetry of neutrino emission?

FV: It should be small: the compact object should be spherical; the transparent atmosphere could not, but the number of emitting centers should stay the same.

O. Saavedra: What about the clocks of Kamiokande-II and Baksan?

FV: For the fit, we use only the relative times of the events, which are reliable. Even in IMB, the time of the arrival of the first neutrino is unknown, since most neutrinos are not detected. We use the fit to evaluate the 3 unknown times intervals: those between the first neutrino and the first event in each detector [11, 8].

C. Pittori: How large is the dead time?

FV: Only IMB has a significant dead time, 0.035 s, and a live-time fraction of 90.55 % [11]. Both are accounted for in the new analysis of SN1987A events [8], and we find *a posteriori* that they have just a minor impact on the fit.

F. Giovannelli: I saw that different number of SN1987A events are occasionally quoted in the literature; can you compare in details with the numbers you give?

FV: Some authors quote $12+8+5=25$ events, including all detected events but in 3 arbitrarily chosen time windows; others quote $11+8=19$ events, excluding Baksan fully and the 6th of the 12 events Kamiokande-II events below the solar neutrino threshold (but not the 3rd just at the threshold); etc. In none of these case, a serious attempt to identify the background events is made. We use instead the 29 events in a minimum bias, larger time window [11, 8], and subsequently calculate the most probable number of signal events using all information we have on the signal and on the background: see Eq. (7). For more discussion, see also [7, 6, 13, 21].

M. Della Valle: What is the limit on neutrino mass from SN1987A?

FV: $5.8 \text{ eV}/c^2$ at 95 % CL [25], about 3 times larger than existing laboratory bound, $2.0 \text{ eV}/c^2$, from Mainz and Troitsk tritium experiments [33]. Despite differences in statistics and in model, this is remarkably close to the result in [11], which makes us confident of the reliability of this limit.